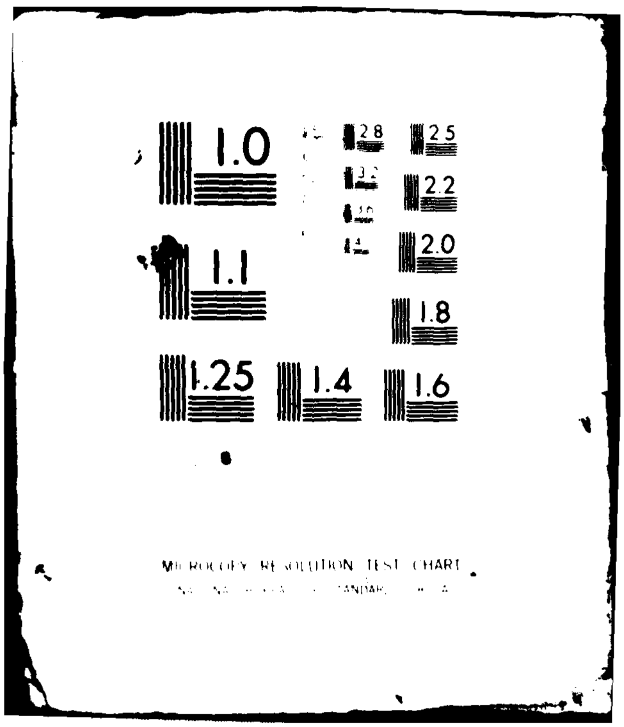
AD-A111 991 SEA-SPACE RESEARCH CO INC MARRERO LA F/G 6/19
RECOMPUTATION OF U. S. NAVY STANDARD AIR DECOMPRESSION TABLES.(U)
JAN 82 P O EDEL N00014-81-C-0216
UNCLASSIFIED NL

1 of 1

END
DATE
FILMED
4-82
DTIC


1.0
2.8
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

RECOMPUTATION OF U. S. NAVY STANDARD AIR DECOMPRESSION TABLES

by

Peter O. Edel

SEA-SPACE RESEARCH COMPANY, INC.
Marrero, Louisiana

The research reported here has been supported under the Office of Naval Research Contract #N00014-81-C-0216 with funds provided by the Naval Medical Research and Development Command.

January 31, 1982

REPORT ON RECOMPUTATION OF U. S. NAVY STANDARD AIR DECOMPRESSION TABLES

ABSTRACT

The U. S. Navy Standard Air Decompression tables were recomputed using the AUTODEC III computer program. Each dive schedule was computed taking into consideration all the standard Navy criteria for controlling decompression for a wide range of physiological variability seen in unacclimitized Naval divers working at a moderate level in cold water. The dive schedules are presented in a standard format with explanation of the considerations used in selecting computer instructions for the various major factors as they are applied for the computation of these schedules.

INTRODUCTION

Current U. S. Navy air decompression schedules represented a significant step forward from their predecessors in safety and scope of operations. However, the requirements for man's activities in the hydrosphere are continually expanding, and recent experience with these schedules shows them to be inadequate or restrictive for both present needs and anticipated future requirements. In the elapsed time since these schedules were constructed, many advances have been made to provide more accurate and more realistic mathematical models for computation and analysis of decompression profiles. Such models utilize computational methods which provide tables which take into account current physiological information in all areas relating to decompression and provide extremely good correlation with manned decompression data from the laboratory and field experiences. One of these methods, known as AUTODEC III, has been applied under this contract to compute a revision of the U. S. Navy Standard Air Decompression Tables. It is believed that this revision will permit increased safety and greater extensions of surface supplied air diving within the U. S. Navy.

BACKGROUND

The scientific study of decompression is less than a century old. Prior to 1900, all one could say with any assurance was that a slower ascent to the surface, following an exposure at elevated pressure, seemed to reduce the problems associated with decompression sickness. It was logical that the British Royal Navy, the most influential sea-power of the time, should have the greatest interest in support of Naval activities with manned deep diving capabilities. Unlike commercial diving operations of the era, which might accept decompression procedures which worked a fair portion of the time, a government agency needed a decompression system which could be relied upon to return the divers to surface pressure, following a hyperbaric exposure without harm in the vast majority of instances. Further, the absence of any mathematical model which could generate such tables required a scientific investigation. Haldane and his co-workers (1) reported the results of their studies of the decompression problem in 1908. Haldane's studies including the experimental data from animal and human exposures, resulted in a model which still serves as a basis for most of the decompression schedules in use today. He assumed that gas would be taken up and eliminated by the body tissues at an exponential rate, based on the assumed rate at which the tissue was perfused. He further concluded that the complicated form in which pressure must be reduced following a hyperbaric exposure required an assumption of several tissue compartments, each with its own rate of gas up take and elimination. Once a gradient was established between the partial pressure of nitrogen in the inspired breathing mixture and nitrogen partial pressure in a given tissue compartment, the gradient will be reduced by 50% in one unit of time which corresponds to a constant for the tissue compartment in question. This unit is referred to as the half-time of the tissue. A second period of time equal to the initial time period will reduce the remaining gradient by 50%, and each subsequent time period will reduce the remainder by 50% from whatever gradient remains at the start of the time period. This can be expressed mathematically by the equations:

$$Pt = \quad ((Pa-Po)\ (1-e^{-kt})): \text{ where}$$

Pt: The [illegible] tissue partial pressure in FSW of nitrogen after an exposure of t minutes.

Po: The original partial pressure in FSW of Nitrogen before the exposure.

Pa:	Partial pressure in FSW on nitrogen in the breathing medium during the exposure.
e:	Base of natural logarithms.
k:	0.693/t 1/2 (tissue rate constant).
t 1/2:	Tissue half time in minutes.
0.693:	Logarithm to the base of 2.
FSW:	Feet Sea Water.

As previously mentioned, Haldane concluded from his experiments that no single half-time tension compartment would suffice to explain the decompression process in man. However, he found that he could represent nitrogen uptake in the body using 5 half-time compartments (5, 10, 20, 40 and 75 minutes). He further postulated that the nitrogen elimination time would be equal to the rate of inert gas uptake in the tissue for any specified tissue compartment.

If this accurately represents inert gas transported in the body, it only remains necessary to determine the amount of excess inert gas which the body tissues can safely attain in order to construct decompression profiles. Based upon experiments, Haldane assumed that the tissues could withstand a pressure reduction to 1/2 of the pressure with which they are equivalent with nitrogen when a man is breathing air. In other words, the tissues would permit a reduction in pressure which would result in a supersaturation ratio of two to one safely (considering air for this purpose to consist of pure nitrogen).

Tables constructed by this method were adopted by the Royal Navy and later by the U. S. Navy as well. In addition to safety and accuracy of prediction of the decompression obligation, the Haldane method introduced the technique of staging the decompression as opposed to a continuous ascent. This provided a practical advantage in increased ease of operation and permitted more accurate control of the diver's decompression. This innovation permitted operation under more adverse conditions. The improvement of the Haldane method over existing systems was soon demonstrated sufficiently to result in its use throughout the world. However, as the use of the tables increased, some flaws in the method became apparent. For example, a 2:1 ratio (in the manner applied by Haldane) will not provide for the decompression obligation resulting from deeper and longer exposures. Haldane (2) later stated that for dives beyond 165 feet, it might be necessary to reduce the ratio further.

In 1935, Hawkins, Shilling and Hansen (3) published an analysis of 2143 no-decompession dives in the depth range of 100 - 200 feet. They proposed that the 5 and 10 minute tissues could tolerate ratios greatly in excess of 2:1 and could safely be ignored. They proposed ratios of 2.8:1 for the 20 minute tissue and 2.0:1 for the 40 and 75 minute tissues but did not actually test tables calculated on that basis.

Later, Yarbrough (4) calculated and tested revised U. S. Navy Standard Air Decompression Tables, using the same three compartments used by Hawkins, Shilling, and Hansen but with the modified ratios shown in Table II:

TABLE II

Tissue Half-Time	Maximum Permissible Ratio
20 min.	1.45:1 to 2.8:1
40 min.	1.75:1 to 2.0:1
75 min.	1.75:1 to 2.0:1

Subsequent evaluation of these schedules by Van Der Aue, et al (5) showed almost 25% decompression sickness incidence when these schedules were applied to working dives involving long exposures. Later work by Van Der Aue, et al (6), in the calculation and testing of surface decompression schedules with oxygen, indicated a requirement for reduction of tissue ratios for deeper dives and the requirement for a value of 120 minutes for the slowest tissue compartment. From this was evolved the ratios shown in Table III:

TABLE III

Tissue Half-Time	Maximum Permissible Ratio
5 min.	3.8:1
10 min.	3.4:1
20 min.	2.8:1
40 min.	2.27:1
75 min.	2.06:1
120 min.	2:1

These ratios were used by Des Grange (7) to develop the present U. S. Navy Standard Air Tables. The above ratios were projected to depth by a formula developed by Dwyer (8) which used a tenth power relationship between tissue supersaturation ratio to surface and at the depth of the decompression stop. Des Grange (9) later developed a method for accounting for the elimination of residual nitrogen remaining in the tissues after completion of a given exposure, during the surface interval between dives, and summing the remaining nitrogen with the additional nitrogen accumulated in a subsequent exposure. Unlike the British method developed by Crocker (10) the U. S. Navy repetitive five tables do not require the use of graphs. Instead, the relative amount of inert gas loading is indicated by letters of the alphabet which increase sequentially to correspond to increased inert gas partial pressure. This method was later adapted by Workman (11) for repetitive mixed gas scuba tables and still later by Edel (12) to develop repetitive tables for NASA's astronauts to permit flying after diving.

In addition to the Standard Air Tables, a set of Exceptional Exposure Air Decompression Tables were computed by Workman (13). Although the Standard Air Tables were tested extensively prior to adoption by the Navy, the testing of the exceptional exposure schedules were limited to the 140 FSW level (for exposures of up to 360 minutes) and the 300 FSW level (for exposure up to one hour). No problems were encountered in manned tests at 300 FSW, but the results at 140 FSW indicated that an average incidence of decompression sickness of 33% could be expected through use of these schedules. This was puzzling, since in addition to the use of conservative supersaturation values which were decreased as projected to depth (and further adjusted during an attempt to reduce the decompression sickness occuring during the test series), half-time of 160 and 240 minutes were used for the slowest tissue compartment. It was not until subsequent work by Markham and Edel (14), and Edel(15) in the development of schedules for decompression following multi-day exposure with nitrogen-oxygen mixtures for use in project Tektite I, that the assumed half-time for the slowest body tissue compartment was found to be much longer than the values used to develop the exceptional exposure tables. Subsequent experiments by Edel (16) to develop decompression schedules for deeper exposure with nitrogen oxygen mixtures in multi-day exposures for project Tektite II, and studies by Edel (17) to determine comparative slowest tissue half-time for various inerts in project Hydrox II, provided the basis for assigning a value of 480 minutes as the value for the slowest half-time compartment for nitrogen. Also, later work by Workman (18) showed that more conservative control values were actually used in the formulation of the U. S. Navy Standard and Exceptional Exposure Tables. Such tables are not, by definition, used

routinely for operational purposes. Hence, statistically significant evidence would not normally be available to indicate a failure of such a schedule to meet the required decompression obligation. One exception to the rule was the 300 FSW/10 min. air schedule which was routinely used by the U. S. Navy for training purposes to expose and familiarize divers to narcosis which involved large numbers of manned exposures over the course of a year. While initial testing of this schedule produced no problems, subsequent use for diver training purposes resulted in an unacceptable level of decompression sickness. The problem was to a large extent corrected by reducing the exposure to between 7 and 9 minutes at 285 FSW and ecompressing according to a schedule for 300 for 10 minutes and subsequently the 290 FSW/20 minute table, (Greene (19)). Although this resulted in a significant improvement, there still remained an undesirable level of bends incidence which subsequently required the replacement of this schedule with an Autodec Table.

The initial failure of the table was, at that time, puzzling in view of the excellent results of the validation testing prior to implementation of the schedule for training purposes. It was not until Hempleman (20), who conducted experiments in which the exposure for a group of associates with these areas. Tables which were grossly inadequate would often cause decompression problems the first time they were applied. Unfortunately, even in commercial diving operations, it may take many years before the majority of depth-time combinations from a particular set of schedules may be applied in the field. Further, the conditions under which they may elapse before sufficient experience (in terms of actual number of dives for a given depth-time combination under a variety of conditions) will provide evidence of the inability of many schedules to adequately provide for the decompression obligation for all conditions. This is especially true of schedules which exceed by smaller margins the decompression safety requirements for which they were designed.

Within the Navy, the problems of evaluation are compounded by limited usage of the full spectrum of schedules available. After an analysis of data from the Naval Safety Center, Berghage and Durman (22) found that the fleet uses only a small fraction of the tables available to them, and that they are generally using the ones for short duration exposures. Hence, the evaluation of the Navy schedules must be based upon exposures which, by comparison with modern mathematical models for decompression schedule computation, are the closest to meeting the decompression obligation.

The usage is not confined to the Navy alone. Mr. Robert Honaker (23) of J & J Marine Diving Company recently analyzed the records of bends incidence of Navy Air Tables used by his divers from over 20,000 exposures. He concluded that adherence to the U. S. Navy Air Tables beyond the "N" repetitive letter designation resulted in an unacceptable incidence of decompression sickness and restricted the use of the tables within his company

beyond that group letter designation. One can assume that the bends incidence for U. S. Navy Air Tables within his company will result in acceptable levels in the future. However, the incidence will be applicable to only a small area of the tables as a whole.

However, even within this range, the direction evaluation of decompression tables though analysis of field experience is complicated by many factors. A major problem is that the tables are rarely used in normal diving operation to the limit of their specified parameters. For example, in tables computed for 10 minute - 10 foot increments, the probability of a given exposure being within one foot or one minute of the schedule limits is only one chance in 10 for either condition. The probability of a particular dive being both within one foot and within one minute of specified limits, in a single exposure, is only one chance in ten for either condition. The probability of a particular dive being both within one foot and within one minute of specified limits, in a single exposure, is only one chance in one hundred. In addition, other factors must be considered. In the rare instance when a dive is performed to the nearest foot and minute of the schedule limits, conditions such as reduced workload, favorable water temperatures, with divers who are relatively resistant to decompression sickness and/or acclimitized, will separately or in combination, serve to reduce the probability of decompression sickness. Hence, the probability of a dive taking place under the maximum and least favorable conditions for which the table was designed can be estimated to be a significantly less than one in one thousand exposures. The presence of such variables, in co bination with the limited area of usage of the air tables, is why many schedules believed to be adequate on the basis of past experience (wherein exposures rarely approached the limiting conditions for a particular depth-time combination) suddenly produce a high bends incidence in a subsequent diving operation in which the balance of factors are less favorable.

Further, field statistics may be artificially lowered by diving practice. Divers and/or diving supervisors who have experienced, or who are aware of the experiences of others, of high incidences of decompression sickness for a particular depth-time combination will later tend to avoid that particular exposure or alter the decompression by "jumping" tables (using a table for a deeper depth and/or longer time than required by the actual exposure. Another example for such a practice is the "two foot-two minute rule" which is applied by many commercial diving companies in addition to the U. S. Navy. In practice, any dive that is made within two feet or two minutes of the tables limits, results in selection of the next deeper or longer schedule (or both if the exposure is within both two feet and two minutes) for decompression.

Some specific attempts have been made to evaluate the U. S. Navy Air tables for specific depth-time combinations. In one case, eleven working dives of 50 minutes duration each, were made to a depth of 210 feet. Following the bottom period, the divers were decompressed in exact accordance with the U. S. Navy decompression schedule for the forgoing exposure. This resulted in a 25% bends in i ence, Linaweaver (24).

Other problem areas are discovered accidentally. Several hospital hyperbaric technicians reported symptoms of decompression sickness after making direct ascents to surface following exposures for 100 at 50 FSW in the hyperbaric chamber. This was not only surprising because the no-decompression dive area was presumed to be one of the safest areas of the air tables but in view of the extremely favorable exposure conditions (dry chamber, normal temperatures, and very low workload by the exposed personnel) (Kindwall (25)). Similarly, other areas of the no-decompression limits such as 70 FSW/50 min. have been reported, Spencer (26).

Although, specific tests such as the above, under carefully controlled conditions, is undeniably the most accurate means of assessing adequacy of decompression procedures, when used with a large number of test subjects, the cost of such evaluation is prohibitive for the schedules as a whole. Further, the large number of subjects required to establish a decompression sickness incidence of 15% or less is, in itself, prohibitive.

A computer evaluation, with a program of demonstratable reliability, is the only practical method of decompression table analysis where a large number of depth-time combination are involved. Such an analysis was recently completed by Edel (27) in which the U. S. Navy air decompression schedules were analyzed (and compared with several U.K. air schedules) using the Autodec method. The analysis agreed with the conclusions of Honaker (23) that the standard air decompression schedule became progressively less adequate as exposure depths and times were increased. The analysis assumed that the divers would be in the lower 25% group of resistance to decompression sickness, within acclimitization, moderate workload, cold water temperatures, and that the schedules would be utilized to the maximum depths and times permitted according to the schedule designations. The result of this analysis indicated that the decompreswas inadequate for reasonable exposure times in dives made below 90 or 100 feet. Even above this leve, the implied exposure limits often required an undesirable restriction of diving operations. Although the U. S. Navy Tables represent a significant advance in the state of the art for the time at which they were developed, they are considerably below the level of what may be accomplished using modern methods of decompression computation.

THE AUTODEC SYSTEM

Calibration Criteria

The principal assumption is made that there are basic scientific laws which can be applied to cover any type of pressure exposure which can conceivably exist. There is not one set of laws to be applied for hyperbaric exposures and another for hypobaric exposures, or one for no-decompression dives, another for dives involving decompression stops, a third for saturation dives, etc. Based upon this assumption, the system is required to take into account all exposures within the framework of its operational usage, providing that accurate information is available to properly and fully describe the profiles in question.

Because of problems in controll, recording and reliability of data, from open water dives, the majority of data was selected from experimental human tests under laboratory conditions. It was considered that a data base containing manned data involving a few thousand exposures involving relatively accurate, complete and reliable information would provide a more reliable foundation than a data base containing tens or hundreds of thousands of manned exposures in which the majority of information was questionable, incomplete, or unreliable. The data base envelope (including and excluding saturation exposures) is provided in Figure #1.

AUTODEC was designed to be a system which could be altered, as necessary, to take advantage of additional data as it becomes available. Such data, depending upon its range of applicability may affect the full range of decompression computations or, more likely, certain areas of computations, for example, exposures involving altitudes, exposures involving very low water temperatures, exposures involving acclimitized subjects. etc. Further, it is possible that the alterations may involve only a portion of any of the above such as: acclimitized subjects for the 2nd and 3rd exposures, or acclimitized subjects after 8 or more exposures, etc. In general, the system is designed to permit updating as new information becomes available to maintain the highest possible accuracy for decompression computations and analysis.

PROCEDURE

FACTOR OR ASSUMPTIONS USED

A. SUBJECT SUSCEPTABILITY

One of the most important factors involved in the computation of decompression computations is the relative susceptability of subjects to decompression sickness. The system permits selection of the susceptability index which in turn affects the criteria for decompression making decompression profiles progressively more conservative as the susceptability index is lowered.

As a result of a lack of specific data to the contrary, it is assumed that for the purposes of decompression computations, there are no significant variations between specific population groups aside from those which result from age and percentage of body fat.

It is strongly suspected, however, that this may be an oversimplification. There may be a "natural selection" process involved in which the types of individuals which select diving as an occupation or pasttime may be within a subgroup of the population as a whole. As an example, individuals who are pale-skinned may tend to avoid living in tropical climates. Hence, a survey of the degree of ultra-violet radiation required to produce sunburn in using people who reside in the Sinai desert may not truly represent the tolerance of the worlds subject population as a whole.

Further, this process may involve changes in the diving subject population as one views different age groups. Very susceptable individuals, who have repeated problems with decompression may voluntary withdraw from diving within a period of time, leaving the remainder of the group more resistant as a whole by comparison with the general population.

In addition, there may be artificial influences in selection of diving candidates and if possible conscious or unconscious "weeding out" of individuals who may have problems with some phase of diving.

Perhaps more important factors may exist between diving groups. As an example, it may be argues that Naval divers are more regulated and supervised in their living habits than their civilian counterparts. They may be expected to, as a group, have more regular habits, better diets, more exercise, and in general be more physically fit than other

diving groups. Hence, if one assumes that physical fitness may be a factor in susceptability to decompession sickness, Naval divers, might possibly be more resistant to decompression sickness as a group than the general population, and other diving groups.

Since, however, there is no supportive data for these assumptions, the computation system does not distinguish between groups, Hence, some variations between predicted response to decompression may result as applied to the Naval diving community. One would suspect that any such variations would result in the direction of increased safety for the population concerned.

B. WORKLOAD

The realization, among divers, that workload is an important factor in decompression probably predates the scientific studies and conclusions in that area. The AUTODEC system is programmed to take this factor into account in rate of inert gas loading. Like Haldane (1), the system assumes that the uptake and elimination rates are reciprocal when no workload is involved. However, it is assumed that the rate is affected by the subjects workload and takes this factor into account in its computation.

C. TEMPERATURE

It is also assumed that temperature is a factor in determining the decompression obligation and is programmed to respond to temperature in the evaluation of the decompression requirements in dives conducted under conditions of reduced temperatures requiring more decompression than those made under warmer temperatures.

D. ACCLIMITIZATION

The program takes into account the effect of pervious exposures made within a relatively short period of time, as acclimitizing the diver and hence making him more resistant to decompression sickness. As

tables are normally constructed with the assumption that they will be used for an "initial" dive for any presumed dive series, this factor is principally utilized in the analysis, rather than the actual computation of dive profiles.

E. OTHER FACTORS

Many factors, (such as tissue tension compartment limits for surface intervals in surface decompression dives, adjustments for sleeping cycles in the chamber, etc.) are not applicable to this mode of operation and hence by default are not considered by the program. The principal factors used, in addition to the operational specifications and constraints for these schedules are as follows:

1. Program: Autodec III
2. Dive file mode: Auto-group (with auto pickup of master dive matrix)
3. Depth-time format (See Table IV)
4. Absolute subject susceptability index: 5%
5. Acclimitization index: 0%
6. Workload index: 50% (Approximately 50% of macimum volunatary workload)
7. Environmental media: water
8. Water temperature index: "cold"
9. Decompression Activity: normal (no sleeping cycles)
10. Pressure measurement: feet-sea-water
11. Dive mode: in-water decompression
12. Base reference pressure: 0 gauge (sea level)
13. Gas supply mode: fixed percentage

14. Breathing mixture at depth: air

15. Maximum rate of descent: 100 feet per minute

16. Breathing mixture during decompression: air

17. Decompression mode: Stage

18. Ascent control to initial stop: 60 FSW per minute, fractional times (in minutes) remaining from ascent to be included in the computation for time at initial stop to result in stage time in minutes as a whole number.

19. Stage increments: 10 FSW

20. Rate of ascent between stages: 1 minute

21. Format stage time printouts: Stage time to be given as actual time at stage plus ascent time from previous stage.

22. Format printout for initial stop: To include stop time and time spent in ascent to initial stop.

23. All other parameters: Autodec III standard

TABLE IV

DEPTH (FSW)	MAX. TIME (MIN.)
40-50	360
60-70	240
80-120	180
130-170	120
180-190	90

Desired time increments for each depth entry (minutes):

5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 120, 180, 240, 360

DATA FILE ENTRIES

A master data file containing the specifications (in AUTODEC code) for recomputation of the U. S. Navy air tables was created and filed on a diskette with a backup copy on a second diskett. The master file contained all information common to the tables as a whole but not specific entries designating the depth and time for each individual dive and the appropriate coded title for the specific depth-time entry. This latter information was contained in a separate and individual file, containing the appropriate information, for each depth-time combination indicated from Table IV. Each file as created was entered on the same diskette(and backup copy) as the master data file. The data entries were checked for possible entry errors and corrections made as required. On completion of this task, the files were ready for processing.

DATA FILE PROECESSING

Each file in turn was picked up by a program supervising file processing and the data forwarded to the appropriate programs for processing. All processing was supervised via screen displays. In the initial stages of evaluation, the displays provided information which confirmed that the appropriate dive file was being processed and that the file data agreed with the above mentioned specifications. In the computation stages, the displays contained information which indicated the decompression was being computed in conformance with the requirements set forth in the specifications. The information was updated for each depth change. In addition, the computed decompression profiles were printed out, as each stage was completed, on hardcopy. The individual hardcopy printouts were then entered into a master schedule in table form for a complete listing of tables in a standard format similar to the form used by the U. S. Navy.

RESULTS

The final schedules are shown in Apendex "A".

SUBJECT INDEX

While the tables were constructed to comply with a 5% subject incidence in compliance with previously mentioned computation specifications, as previously mentioned there are good reasons to suspect that Naval divers, as a group, may be less susceptable to decompression sickness then their civiliam counterparts. Hence, schedules with this specification may be slightly more conservative than indicated by the subject index. In addition, depth-time "blocking" may serve to increase the safety margin in the majority of schedules. If for example, the computer determines that an ascent to an initial stop of 30 FSW is in violation of the programmed decompression criteria for such an exposure the ascent to 30 FSW is not permitted and an ascent to 40 FSW is made (assuming the latter to be safe within the programmed constraints). However, if an ascent to 30.0001 FSW would not violate the safety criteria, a significant increase in safety in excess of programmed requirements for 5% subject index will result from the additional depth of the decompression stop being close to 10 FSW in excess of the actual requirement computed by the system.

This also applies to the time spent at the stop as well. If, at the 20 FSW stop, the computed requirement calls for a 1.001 minute stay at that depth prior to ascending to the 10 FSW stop, a one minute decompression stop is denied and a two minute decompression stop is utilized. In this case the time would result in almost double the actual time judged necessary by the program and an appreciable increase, in accordance with programmed criteria, to decompression safety. Hence, the majority of the tables should offer greater safety then would be indicated by the subject index level selected.

It is always assumed that persons with abnormal conditions are not permitted to dive. In general, it would be rare that an individual in this category would desire, or be permitted, to dive. However, it has been noticed on a number of occasions that unusual susceptability to decompression sickness may result in persons who have had injuries

requiring surgical intervention (especially in the areas of the knees). Some individuals in this group may have special problems with use of decompression schedules in general.

It must be recognized that even with the most modern methods of decompression table computation, decompression sickness cannot be eliminated completely with a single set of schedules that can be realistically applied to operational requirements. Conversely, any schedule which is safe for one segment of the diving population, must be overly conservative for the remainder. A table which would adequately provide for the decompression obligation for 90% of the divers would be overconservative for 80% and result in decompression sickness for 10%. Hence, if decompression sickness is to be controlled to an acceptable minimum, the vast majority of divers must accept a schedule which is, to them, overly conservative.

WORKLOAD

A comparison of tasks accomplished underwater with those in the test chamber has resulted in the conclusion that, in the vast majority of cases, an underwater workload of 50% of that which may be voluntarily achieved in a test chamber is the maximum that will be required for open water operations. Providing for a greater workload would be necessarily restrictive and hence a 50% workload factor was chosen for this task. On unusual occasions wherein an unusually severe workload may be required in open water diving, the effect of such a workload may be compensated for by decompressing on a table which would be used for the next greatest depth or time than that indicated by the divers actual exposure.

TEMPERATURE

It is assumed that, while many operations may take place in "cold" water, the vast majority of open water divers will not involve "fridgid" water temperatures. Hence, the provision was made for computation of schedules for "cold", but not "fridgid" water temperatures. For dives made in unusually cold waters, the additional decompression obligation may be compensated for by decompressing on a table for the next greater depth or time than indicated for the actual exposure.

ACCLIMITIZATION

It is assumed, as would be expected to be the case for the majority of Naval dives, that the divers are not acclimitized by prior exposures and the tables were constructed for this conditon. This would suggest that no tests of such tables be made by individuals who have been significantly acclimitized by prior exposures. Review of past experiments, suggest that subjects who are exposed at weekly intervals do not appear to demonstrate any appreciable effects of acclimitization.

M-VALUE MATRIX

It must be stated that the AUTODEC system does not use a M-Value Matrix as such. Hence, the following table is only a translation of criteria (for the specific requirements of this task) which is represented in the conventional format. These values would be exceeded for other conditions but would not be exceeded for the specific profiles used and the computer is programmed to apply lesser values as required. Hence, this is not provided as an accurate representation of AUTODEC criteria but rather as a translation of this criteria into conventional terms for the purposes of illustration. It is analogous to an attempt to provide a fixed ratio which represents a M-Value Matrix. One may select the highest ratio which would result from use of tables, but this would not be considered an accurate representation of an M-Value System as such. It should be stated that conventional application of this Matrix to compute decompression tables would be expected to produce a relatively high incidence of decompression sickness for most depth-time combinations.

The 13 compartments shown were involved in these computations. Longer half-time compartments are contained in the programming but were not invoked for the requirements of this study.

TABLE V

Arrival	(compartment half-times)												
Depths	5	6.5	8	12	17	25	40	60	75	100	140	180	265
0	102	96	88	80	73	65	57	54	51	48	46	45	44.5
10	123	115	107	98	89	81	71	68	65	61	59	58	57.5
20	143	134	125	115	105	95	85	81	78	74	72	71	70
30	162	152	142	131	121	110	99	94	91	87	84	83	82
40	180	170	160	147	136	125	112	108	104	100	96	95	94
50	199	187	175	162	151	139	125	120	116	112	108	107	106
60	215	204	190	178	165	153	139	133	129	125	120	119	118
70	232	220	207	193	180	167	152	146	142	137	132	131	130
80	249	236	224	208	194	180	165	159	154	149	144	143	142
90	266	252	238	223	208	194	178	172	166	161	156	155	154
100	282	268	253	238	222	207	190	184	178	174	168	167	166

SUMMARY

The U. S. Navy Standard Air Decompression tables were recomputed using the AUTODEC computer program. Each dive schedule was computed taking into consideration all the standard Navy criteria for controlling decompression for wide range of physiological variability seen in unacclimitized Naval Divers working at a moderate level in cold water. The dive schedules are presented in a standard format with explanation of the considerations used in selecting computer instructions for the various major factors as they are applied for the computation of these schedules.

REFERENCES

1: Boycott, A. E., Damant, G.C.C., & Haldane, J. S. (1908). The Prevention of Compressed Air Illness. J. Hyg. Lond. 8, 342-443

2. Haldane, J.S. and Priestly, J.G. Resperation, new ed. New Haven, Yale University Press, 1935.

3. Hawkins, J.A., Shilling, C.S., and Hansen, R.A. A suggested Change in Calculating Decompression Tables for Diving. U. S. Navy Medical Bull. 33, 327-338, 1935.

4. Yarbrough, O.D., Calculation of Decompression Tables. Research Reprot. U. S. Navy Experimental Diving Unit, Washington, D.C. 1937.

5. Van Der Aue, O.E., Brinton, E.S., and Keller, R. J., (1945). Surface Decompression, Derivation and Testing of Decompression and the use of Oxygen. Research report 1. U. S. Navy Experimental Diving Unit Washington, D.C., 1951.

6. Van Der Aue, O.E., Keller, R. J., Brinton, E. S., Barron, G., Gilliam, H.D. and Jones, R.J., Calculating and Testing of Decompression and the Use of Oxygen. Research report 1. U. S. Navy Experimental Diving Unit, Washington, D.C., 1951.

7. Des Ganges, M. (1956). Standard Air Decompression Tables. Research Report 5-57, U. S. Navy Experimental Diving Unit, Washington, D.C.

8. Dwyer, J.V. (1956). Calculation of Repetitive Diving Decompression Tables. Research report 5-57, U. S. Navy Experimental Diving Unit Washington, D.C.

9. Des Granges, M. (1957). Repetitive Diving Decompression Tables. Research report 6-57, U. S. Navy Experimental Diving Unit, Washington, D.C.

10. Crocker, W.E. (1958). Proposals for Applying the New Standard Tables to Surface Decompression and Combined Dives. M.R.C. (RNPRC) Report UPS 175.

11. Workman, R.D., and Reynolds, J.L. (1965). Adaptation of Helium-Oxygen to Mixed Gas Scuba. Research report 1-65. U. S. Navy Experimental Diving Unit, Washington, D.C.

12. Edel, P.O. (June 30, 1971). Computer controlled Decompression Procedures in Hyperbaric, Hypobaric Profiles. Contract #NNAS 9-9036.

13. Workman, R.D. (1957). Calculation of Air Saturation Decompression Tables. Research report 11-57. U. S. Navy Experimental Diving Unit, Washington, D.C.

14. Markham, T.N., and Edel, P.O. "Decompression", PROJECT TEKTITE I. A Multi-Agency Dive Conducted by the United States Navy, The National Aeronautics and Space Administration, the Department of the Interior, and the General Electric Company, eds. D.C. Pauli & H.A. Cole, Office of Naval Research Report DR 153, Washington, D.C.

15. Edel, P.O. 'Deliniation of Emergency Surface Decompression and Treatment Procedures for PROJECT TEKTITE Aquanauts". Aerospace Med. (42), June, 1971 pp. 616-621.

16. Edel, P.O. "Experiments to Determine Decompression Tables for the TEKTITE 100 FSW Mission", Report to the U. S. Department of the Interior, J. & J. Marine Diving Co., Inc. (March 31, 1971).

17. Edel, P.O. "PROJECT HYDROX" in Underwater 1975; Proceedings of the Fourth World Congress of Underwater Activities. Adolfson, J., ed. Vol II, pp 503-513. Stockholm, Sweden, Almqvist & Wiskell International, 1976.

18. Workman, R.D. (1965). Calculation of Decompression Schedules for Nitrogen-Oxygen and Helium-Oxygen Dives. Research report 6-65. Navy Experimental Diving Unit, Washington, D.C.

19. Greene, K.M. personal communication (1981)

20. Hempleman, H.V. (1967). Decompression procedures for deep, open sea operations in proceedings Third Underwater Physiology Symposium. Ed. Lambertsen, C.J. pp. 255-266. Baltimore: Williams & Wilkins.

21. Edel, P.O. (March 31, 1981) Apendex "E" "Interim Decompression Tables for Caison/Tunnel Work for Compressed Air", Report to National Institute of Occupational Safety & Health. Sea-Space Research Company, Harvey, Louisiana.

22. Berghage, T.E. & Durman, D. (1980). U. S. Navy Air Decompression Schedule Risk Analysis. Report to Navy Medical Research and Development Command. Naval Medical Research Institute, Bethesda, Maryland.

23. Hornaker, P. personal communication 1980.

24. Linaweaver, P.G.

25. Kindwall, E.P. personal communication July 1981.

26. Spencer, M.P., Johanson, D.C., & Campbell, S.D. Safe Decompression with the Doppler Ultrasonic Blood Bubble Detector. in: Lambertsen, C.J., ed. Underwater Physiology V. Proceedings of the Fifth Symposium on Underwater Physiology, P. 311-325. Bethesda, Md., Federation of American Societies for Experimental Biology, 1976.

27. Edel, P.O. Analysis of Decompression Tables Calculated by Non-U.S. Navy Methods. Report to Office of Naval Research. Sea-Space Research Company, Harvey, La. March 31, 1980.

AUTODEC III: STANDARD AIR EXPOSURE TABLES (1982)

NOTE: THESE TABLES ARE UNTESTED AS OF JANUARY 31, 1982

DEPTH	TOB	[D E C O M P R E S S I O N	S T O P S	]	TOTAL TIME
FSW	min.			10	Hrs./min.
30	300				0:0.5
30	360			11	0:11
FSW	min.			10	Hrs./min.
40	120				0:0.67
40	180			11	0:11
40	240			46	0:46
40	360			101	1:41
FSW	min.		20	10	Hrs./min.
50	70				0:0.83
50	80			6	0:06
50	90			11	0:11
50	120			21	0:21
50	180			71	1:11
50	240			121	2:01
50	360		46	151	3:17
FSW	min.		20	10	Hrs./min.
60	50				0:01
60	60			11	0:11
60	70			16	0:16
60	80			21	0:21
60	90			26	0:26
60	120			51	0:51
60	180		21	121	2:22
60	240		46	151	3:17
FSW	min.	30	20	10	Hrs./min.
70	30				0:1.16
70	40			5	0:05
70	50			16	0:16
70	60			21	0:21
70	70			31	0:31
70	80		6	31	0:37
70	90		11	41	0:52
70	120		31	71	1:42
70	180	6	51	151	3:28
70	240	21	91	211	5:23

AUTODEC STANDARD AIR EXPOSURE TABLES (contd)

DEPTH FSW	TOB min.	[DECOMPRESSION STOPS] 30	20	10	TOTAL TIME Hrs./min.
					0:1.33
80	25			5	0:05
80	30			17	0:17
80	40			22	0:22
80	50		3	31	0:34
80	60		11	41	0:52
80	70		16	41	0:57
80	80		21	61	1:22
80	90	11	41	101	2:33
80	120	31	81	181	4:53
80	180				

FSW	min.	40	30	20	10	Hrs./min.
						0:01.5
90	20				7	0:07
90	25				9	0:09
90	30			5	21	0:26
90	40			6	26	0:32
90	50			12	36	0:48
90	60			22	41	1:03
90	70		11	26	61	1:38
90	80		16	31	81	2:08
90	90		21	46	151	3:38
90	120	16	46	121	181	6:04
90	180					

FSW	min.	50	40	30	20	10	Hrs./min.
							0:01.7
100	20					12	0:12
100	25				3	11	0:14
100	30				7	21	0:28
100	40				17	31	0:48
100	50			7	21	41	1:09
100	60			12	31	61	1:44
100	70			17	31	91	2:19
100	80			22	41	101	2:44
100	90		16	31	71	151	4:29
100	120	11	31	61	121	241	7:45
100	180						

AUTODEC STANDARD AIR EXPOSURE TABLES (contd)

DEPTH	TOB	[DECOMPRESSION			STOPS		]	TOTAL TIME
FSW	min.		50	40	30	20	10	Hrs./min.
110	15							0:1.83
110	20					4	8	0:12
110	25					4	11	0:15
110	30					7	21	0:28
110	40				4	16	31	0:51
110	50				9	21	41	1:11
110	60				17	26	61	1:44
110	70			9	21	31	91	2:32
110	80			12	31	41	121	3:25
110	90			17	31	46	151	4:05
110	120		11	21	41	81	181	5:35
110	180		21	41	91	151	241	9:05
FSW	min.	60	50	40	30	20	10	Hrs./min.
120	10							0:02
120	15					3	4	0:07
120	20					4	11	0:15
120	25					7	16	0:23
120	30				4	11	21	0:36
120	40				9	16	41	1:06
120	50			7	16	21	51	1:35
120	60			9	21	31	71	2:12
120	70			17	21	41	101	3:00
120	80		5	21	31	41	151	4:09
120	90		9	21	31	61	151	4:33
120	120		22	31	46	121	181	6:41
120	180	16	41	46	121	181	301	11:46
FSW	min.	60	50	40	30	20	10	Hrs./min.
130	10							0:2.16
130	15					4	6	0:10
130	20				4	6	11	0:21
130	25				5	11	16	0:32
130	30			3	8	11	31	0:53
130	40			7	11	21	41	1:20
130	50		5	11	16	31	61	2:04
130	60		7	16	21	36	101	3:02
130	70		9	21	26	46	121	3:43
130	80		17	21	31	61	151	4:41
130	90	7	21	21	41	71	151	5:12
130	120	17	21	41	61	121	211	7:52

AUTODEC STANDARD AIR EXPOSURE TABLES (contd)

DEPTH FSW	TOB min.	DECOMPRESSION STOPS 80	70	60	50	40	30	20	10	TOTAL TIME Hrs./min.
140	5									2:33
140	10							3	4	0:07
140	15							7	6	0:13
140	20						5	11	11	0:27
140	25					4	6	11	16	0:37
140	30					7	11	11	31	1:00
140	40				5	11	11	31	41	1:39
140	50				7	11	21	31	81	2:31
140	60			4	11	16	26	41	121	3:39
140	70			8	11	21	31	46	151	4:28
140	80			9	16	26	41	71	181	5:44
140	90			12	21	31	41	91	181	6:17
140	120		12	16	31	41	61	151	241	9:1[illegible]
FSW	min.	80	70	60	50	40	30	20	10	Hrs./min.
150	5									0:2.5
150	10							4	4	0:08
150	15						5	6	11	0:22
150	20					5	6	11	11	0:33
150	25				4	4	6	11	26	0:51
150	30				4	6	11	16	41	1:18
150	40			5	6	11	16	31	61	2:10
150	50			7	11	16	21	41	121	3:37
150	60			9	11	21	31	61	151	4:44
150	70		5	11	16	21	36	71	151	5:11
150	80		7	16	16	31	41	91	181	6:23
150	90		12	16	21	31	51	121	181	7:13
150	120	7	16	21	31	46	91	181	241	10:34
FSW	min.	80	70	60	50	40	30	20	10	Hrs./min.
160	5									0:2.66
160	10						4	3	6	0:13
160	15					4	4	6	11	0:25
160	20				4	4	6	11	11	0:36
160	25				5	6	6	16	31	1:04
160	30			4	6	6	11	21	41	1:29
160	40			7	6	11	21	31	71	2:27
160	50		4	7	11	16	31	41	121	3:51
160	60		7	11	16	21	31	61	151	4:58
160	70		9	11	21	21	41	91	181	6:15
160	80	5	11	16	21	31	51	121	181	7:[illegible]7
160	90	7	16	16	21	41	61	121	211	8:14
160	120	17	16	26	31	61	101	181	201	12:14

AUTODEC STANDARD AIR EXPOSURE TABLES (contd)

DEPTH FSW	TOB min.	90	80	70	60	50	40	30	20	10	TOTAL TIME Hrs./min.
		[D E C O M P R E S S I O N						S T O P S		]	
170	5										0:2.83
170	10						4	3	3	6	0:16
170	15					4	3	4	6	11	0:28
170	20				3	3	4	11	11	21	0:53
170	25				5	6	6	11	16	31	1:15
170	30			4	4	6	6	16	21	61	1:58
170	40			5	6	11	11	21	31	91	2:56
170	50		4	6	11	11	21	31	51	121	4:16
170	60		5	11	11	16	21	36	71	181	5:52
170	70		7	11	16	21	26	41	101	181	6:44
170	80		9	16	16	21	31	61	121	211	8:06
170	90	5	11	16	16	31	41	81	121	241	9:23
170	120	12	16	16	31	41	61	121	181	361	14:00

FSW	min.	90	80	70	60	50	40	30	20	10	Hrs./min.
180	5									5	0:05
180	10						4	3	4	6	0:17
180	15					5	3	4	11	11	0:34
180	20				4	4	6	11	11	26	1:02
180	25			4	4	6	6	11	21	36	1:28
180	30			5	6	6	11	16	31	61	2:16
180	40		5	6	6	11	16	21	41	101	3:27
180	50		7	6	11	16	21	31	61	151	5:04
180	60	4	6	11	11	21	[illegible]	41	91	181	6:27
180	70	5	11	11	16	21	31	61	121	181	7:38
180	80	7	11	16	21	21	[illegible]	61	151	241	9:30
180	90	12	11	16	21	31	41	91	151	301	11:15

FSW	min.	100	90	80	70	60	50	40	30	20	10	Hrs./min.
190	5									4	3	0:07
190	10						4	3	3	4	6	0:20
190	15					4	3	3	4	11	11	0:36
190	20				4	3	4	6	11	11	31	1:10
190	25				5	6	6	6	11	21	41	1:36
190	30			4	4	6	6	11	16	31	61	2:19
190	40		3	6	6	6	11	16	31	41	121	4:01
190	50		5	6	11	11	16	21	41	71	151	5:33
190	60		7	11	11	11	21	26	41	101	181	6:50
190	70	4	8	11	11	16	26	31	61	121	211	8:20
190	80	7	11	11	16	21	26	41	81	151	241	10:06
190	90	9	11	11	16	31	31	51	101	151	301	11:53